

# Bound energy for the exponential-cosine-screened Coulomb potential

Sameer M. Ikhdaïr\* and Ramazan Sever†

\**Department of Physics, Near East University, Nicosia, North Cyprus, Mersin-10, Turkey*

†*Department of Physics, Middle East Technical University, 06531 Ankara, Turkey.*

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## Abstract

An alternative approximation scheme has been used in solving the Schrödinger equation for the exponential-cosine-screened Coulomb potential. The bound state energies for various eigenstates and the corresponding wave functions are obtained analytically up to the second perturbation term.

Keywords: Exponential-cosine-screened Coulomb potential, Perturbation theory

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## I. INTRODUCTION

The generalized exponential-cosine-screened Coulomb (GECSC) potential or the generalized cosine Yukawa (GCY) potential:

$$V(r) = -\left(\frac{A}{r}\right) \exp(-\delta r) \cos(g\delta r), \quad (1)$$

where  $A$  is the strength coupling constant and  $\delta$  is the screening parameter, is known to describe adequately the effective interaction in many-body environment of a variety of fields

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\*sameer@neu.edu.tr

†sever@metu.edu.tr

such as atomic, nuclear, solid-state, plasma physics and quantum field theory [1,2]. It is also used in describing the potential between an ionized impurity and an electron in a metal [3,4] or a semiconductor [5] and the electron-positron interaction in a positronium atom in a solid [6]. The potential in (1) with  $g = 1$  is known as a cosine-screened Coulomb potential. The static screened Coulomb (SSC) potential ( $g = 0$  case) is well represented by Yukawa form:  $V(r) = -(\alpha Ze^2) \exp(-\delta r)/r$  which emerges as a special case of the ECSC potential in (1) with  $A = \alpha Ze^2$ , where  $\alpha = (137.037)^{-1}$  is the fine-structure constant and  $Z$  is the atomic number, is often used for the description of the energy levels of light to heavy neutral atoms [7]. It is known that SSC potential yields reasonable results only for the innermost states when  $Z$  is large. However, for the outermost and middle atomic states, it gives rather poor results. Although the bound state energies for the SSC potential with  $Z = 1$  have been studied [7].

The Schrödinger equation for such a potential does not admit exact solutions. So various approximate methods [8] both numerical and analytical have been developed. Hence, the bound-state energies of the ECSC potential were first calculated for the  $1s$  state using numerical [3,8,9] and analytical [10,11] methods and for the  $s$  states by a variational method [12]. Additionally, the energy eigenvalues of the ECSC potential [13] have been recalculated for the  $1s$  state with the use of the ground-state logarithmic perturbation theory [14,15] and the Padé approximant method. The problem of determining the critical screening parameter  $\delta_c$  for the  $s$  states was also studied [16].

It has also been shown that the problem of screened Coulomb potentials can be solved to a very high accuracy [17] by using the hypervirial relations [18,19,20] and the Padé approximant method. The bound-state energies of the ECSC potential for all eigenstates were accurately determined within the framework of the hypervirial Padé scheme [21]. Further, the large- $N$  expansion method of Mlodinow and Shatz [22] was also applied to obtain the energies of the ground and first excited  $s$ -states and the corresponding wave functions. Recently, we studied the bound-states of the ECSC potential for all states using the shifted large  $N$ -expansion technique [23].

In this paper, we investigate the bound-state properties of ECSC potential using a new perturbative formalism [24] which has been claimed to be very powerful for solving the Schrödinger equation to obtain the bound-state energies as well as the wave functions in Yukawa or SSC potential problem [24,25] in both bound and continuum regions. This novel treatment is based on the decomposition of the radial Schrödinger equation into two pieces having an exactly solvable part with an additional piece leading to either a closed analytical solution or approximate treatment depending on the nature of the perturbed potential.

The contents of this paper is as follows. In section II we briefly outline the method with all necessary formulae to perform the current calculations. In section III we apply the approach to the Schrödinger equation with the ECSC potential and present the results obtained analytically and numerically for the bound-state energy values. Finally, in section IV we give our concluding remarks.

## II. THE METHOD

For the consideration of spherically symmetric potentials, the corresponding Schrödinger equation, in the bound state domain, for the radial wave function reads

$$\frac{\hbar^2}{2m} \frac{\psi_n''(r)}{\psi_n(r)} = V(r) - E_n, \quad (2)$$

with

$$V(r) = \left[ V_0(r) + \frac{\hbar^2}{2m} \frac{\ell(\ell+1)}{r^2} \right] + \Delta V(r), \quad (3)$$

where  $\Delta V(r)$  is a perturbing potential and  $\psi_n(r) = \chi_n(r)u_n(r)$  is the full radial wave function, in which  $\chi_n(r)$  is the known normalized eigenfunction of the unperturbed Schrödinger equation whereas  $u_n(r)$  is a moderating function corresponding to the perturbing potential.

Following the prescription of Ref. 24, we may rewrite (2) as

$$\frac{\hbar^2}{2m} \left( \frac{\chi_n''(r)}{\chi_n(r)} + \frac{u_n''(r)}{u_n(r)} + 2 \frac{\chi_n'(r)u_n'(r)}{\chi_n(r)u_n(r)} \right) = V(r) - E_n. \quad (4)$$

The logarithmic derivatives of the unperturbed  $\chi_n(r)$  and perturbed  $u_n(r)$  wave functions are given by

$$W_n(r) = -\frac{\hbar}{\sqrt{2m}} \frac{\chi'_n(r)}{\chi_n(r)} \quad \text{and} \quad \Delta W_n = -\frac{\hbar}{\sqrt{2m}} \frac{u'_n(r)}{u_n(r)}, \quad (5)$$

which leads to

$$\frac{\hbar^2}{2m} \frac{\chi''_n(r)}{\chi_n(r)} = W_n^2(r) - \frac{\hbar}{\sqrt{2m}} W'_n(r) = \left[ V_0(r) + \frac{\hbar^2}{2m} \frac{\ell(\ell+1)}{r^2} \right] - \varepsilon_n, \quad (6)$$

where  $\varepsilon_n$  is the eigenvalue for the exactly solvable potential of interest, and

$$\frac{\hbar^2}{2m} \left( \frac{u''_n(r)}{u_n(r)} + 2 \frac{\chi'_n(r) u'_n(r)}{\chi_n(r) u_n(r)} \right) = \Delta W_n^2(r) - \frac{\hbar}{\sqrt{2m}} \Delta W'_n(r) + 2W_n(r) \Delta W_n(r) = \Delta V(r) - \Delta \varepsilon_n, \quad (7)$$

in which  $\Delta \varepsilon_n = E_n^{(1)} + E_n^{(2)} + \dots$  is the correction term to the energy due to  $\Delta V(r)$  and  $E_n = \varepsilon_n + \Delta \varepsilon_n$ . If Eq. (7), which is the most significant piece of the present formalism, can be solved analytically as in (6), then the whole problem, in Eq. (2) reduces to the following form

$$[W_n(r) + \Delta W_n(r)]^2 - \frac{\hbar}{\sqrt{2m}} (W_n(r) + \Delta W_n(r))' = V(r) - E_n, \quad (8)$$

which is a well known treatment within the frame of supersymmetric quantum theory (SSQT) [26]. Thus, if the whole spectrum and corresponding eigenfunctions of the unperturbed interaction potential are known, then one can easily calculate the required superpotential  $W_n(r)$  for any state of interest leading to direct computation of related corrections to the unperturbed energy and wave function.

For the perturbation technique, we can split the given potential in Eq.(2) into two parts. The main part corresponds to a shape invariant potential, Eq. (6), for which the superpotential is known analytically and the remaining part is treated as a perturbation, Eq. (7). Therefore, it is obvious that ECSC potential can be treated using this prescription. In this case, the zeroth-order term corresponds to the Coulomb potential while higher-order terms constitute the perturbation. However, the perturbation term in its present form cannot

be solved exactly through Eq. (7). Thus, one should expand the functions related to the perturbation in terms of the perturbation parameter  $\lambda$ ,

$$\Delta V(r; \lambda) = \sum_{i=1}^{\infty} \lambda_i V_i(r), \quad \Delta W_n(r; \lambda) = \sum_{i=1}^{\infty} \lambda_i W_n^{(i)}(r), \quad E_n^{(i)}(\lambda) = \sum_{i=1}^{\infty} \lambda_i E_n^{(i)}, \quad (9)$$

where  $i$  denotes the perturbation order. Substitution of the above expansions into Eq. (7) and equating terms with the same power of  $\lambda$  on both sides up to  $O(\lambda^3)$  gives

$$2W_n(r)W_n^{(1)}(r) - \frac{\hbar}{\sqrt{2m}} \frac{dW_n^{(1)}(r)}{dr} = V_1(r) - E_n^{(1)}, \quad (10)$$

$$W_n^{(1)2}(r) + 2W_n(r)W_n^{(2)}(r) - \frac{\hbar}{\sqrt{2m}} \frac{dW_n^{(2)}(r)}{dr} = V_2(r) - E_n^{(2)}, \quad (11)$$

$$2 \left[ W_n(r)W_n^{(3)}(r) + W_n^{(1)}(r)W_n^{(2)}(r) \right] - \frac{\hbar}{\sqrt{2m}} \frac{dW_n^{(3)}(r)}{dr} = V_3(r) - E_n^{(3)}. \quad (12)$$

Hence, unlike the other perturbation theories, Eq. (7) and its expansion, Eqs. (10-12), give a flexibility for the easy calculations of the perturbative corrections to energy and wave functions for the  $n$ th state of interest through an appropriately chosen perturbed superpotential.

### III. APPLICATION TO THE ECSC POTENTIAL

Considering the recent interest in various power-law potentials in the literature, we work through the article within the frame of low screening parameter. In this case, the ECSC potential can be expanded in power series of the screening parameter  $\delta$  as [10]

$$V(r) = - \left( \frac{A}{r} \right) \exp(-\delta r) \cos(\delta r) = - \left( \frac{A}{r} \right) \sum_{i=0}^{\infty} V_i(\delta r)^i, \quad (13)$$

where the perturbation coefficients  $V_i$  are given by

$$V_1 = -1, \quad V_2 = 0, \quad V_3 = 1/3, \quad V_4 = -1/6, \quad V_5 = 1/30, \dots \quad (14)$$

We now apply this approximation method to the ECSC potential with the angular momentum barrier

$$V(r) = -\left(\frac{A}{r}\right) e^{-\delta r} \cos(\delta r) + \frac{\ell(\ell+1)\hbar^2}{2mr^2} = \left[V_0(r) + \frac{\ell(\ell+1)\hbar^2}{2mr^2}\right] + \Delta V(r), \quad (15)$$

where the first piece is the shape invariant zeroth-order which is an exactly solvable piece corresponding to the unperturbed Coulomb potential with  $V_0(r) = -A/r$  while  $\Delta V(r) = A\delta - (A\delta^3/3)r^2 + (A\delta^4/6)r^3 - (A\delta^5/30)r^4 + \dots$  is the perturbation term. The literature is rich with examples of particular solutions for such power-law potentials employed in different fields of physics, for recent applications see Refs. [27,28]. At this stage one may wonder why the series expansion is truncated at a lower order. This can be understood as follows. It is widely appreciated that convergence is not an important or even desirable property for series approximations in physical problems. Specifically, a slowly convergent approximation which requires many terms to achieve reasonable accuracy is much less valuable than the divergent series which gives accurate answers in a few terms. This is clearly the case for the ECSC problem [29]. However, it is worthwhile to note that the main contributions come from the first three terms. Thereby, the present calculations are performed up to the second-order involving only these additional potential terms, which suprisingly provide highly accurate results for small screening parameter  $\delta$ .

### A. Ground State Calculations ( $n = 0$ )

In the light of Eq. (6), the zeroth-order calculations leading to exact solutions can be carried out readily by setting the ground-state superpotential and the unperturbed exact energy as

$$W_{n=0}(r) = -\frac{\hbar}{\sqrt{2m}} \frac{\ell+1}{r} + \sqrt{\frac{m}{2}} \frac{A}{(\ell+1)\hbar}, \quad E_n^{(0)} = -\frac{mA^2}{2\hbar^2(n+\ell+1)^2}, \quad n = 0, 1, 2, \dots \quad (16)$$

and from the literature, the corresponding normalized Coulomb bound-state wave function [30]

$$\chi_n(r) = N_{n,l}^{(C)} r^{\ell+1} \exp[-\beta r] \times L_n^{2\ell+1}[2\beta r], \quad (17)$$

in which  $N_{n,l}^{(C)} = \left[ \frac{2mA}{(n+\ell+1)\hbar^2} \right]^{\ell+1} \frac{1}{(n+\ell+1)} \frac{1}{\sqrt{\frac{\hbar^2}{mA}!(n+2\ell+1)!}}$  is a normalized constant,  $\beta = \frac{mA}{(n+\ell+1)\hbar^2}$  and  $L_n^k(x) = \sum_{m=0}^n (-1)^m \frac{(n+k)!}{(n-m)!(m+k)!m!} x^m$  is an associate Laguarre polynomial function [31].

For the calculation of corrections to the zeroth-order energy and wavefunction, one needs to consider the expressions leading to the first- and second-order perturbation given by Eqs. (10–12). Multiplication of each term in these equations by  $\chi_n^2(r)$ , and bearing in mind the superpotentials given in Eq. (5), one can obtain the straightforward expressions for the first-order correction to the energy and its superpotential:

$$E_n^{(1)} = \int_{-\infty}^{\infty} \chi_n^2(r) \left( -\frac{A\delta^3}{3} r^2 \right) dr, \quad W_n^{(1)}(r) = \frac{\sqrt{2m}}{\hbar} \frac{1}{X_n^2(r)} \int^r \chi_n^2(x) \left[ E_n^{(1)} + \frac{A\delta^3}{3} x^2 \right] dx, \quad (18)$$

and also for the second-order correction and its superpotential:

$$E_n^{(2)} = \int_{-\infty}^{\infty} \chi_n^2(r) \left[ \frac{A\delta^4}{6} r^3 - W_n^{(1)2}(r) \right] dr, \\ W_n^{(2)}(r) = \frac{\sqrt{2m}}{\hbar} \frac{1}{X_n^2(r)} \int^r \chi_n^2(x) \left[ E_n^{(2)} + W_n^{(1)2}(x) - \frac{A\delta^4}{6} x^3 \right] dx, \quad (19)$$

for any state of interest. The above expressions calculate  $W_n^{(1)}(r)$  and  $W_n^{(2)}(r)$  explicitly from the energy corrections  $E_n^{(1)}$  and  $E_n^{(2)}$  respectively, which are in turn used to calculate the moderating wave function  $u_n(r)$ .

Thus, through the use of Eqs. (18) and (19), after some lengthy and tedious integrals, we find the zeroth order energy shift and their moderating superpotentials as

$$E_0^{(1)} = -\frac{\hbar^4 (\ell+1)^2 (\ell+2) (2\ell+3)}{6Am^2} \delta^3, \\ E_0^{(2)} = \frac{\hbar^6 (\ell+1)^3 (\ell+2) (2\ell+3) (2\ell+5)}{24A^2m^3} \delta^4 \\ - \frac{\hbar^{10} (\ell+1)^6 (\ell+2) (2\ell+3) (8\ell^2+37\ell+43)}{72A^4m^5} \delta^6, \\ W_0^{(1)}(r) = -\frac{\hbar (\ell+1) \delta^3 r}{3\sqrt{2m}} \left\{ r + \frac{\hbar^2 (\ell+1) (\ell+2)}{Am} \right\}, \\ W_0^{(2)}(r) = -\frac{\hbar \delta^4 cr}{2\sqrt{2m}} \left\{ \delta^2 r^3 + ar^2 + b \left[ r + \frac{\hbar^2 (\ell+1) (\ell+2)}{Am} \right] \right\} - \frac{\hbar (\ell+1)}{\sqrt{2mA}} E_0^{(2)}, \quad (20)$$

in which

$$a = \frac{\hbar^2(\ell+1)(3\ell+7)\delta^2}{Am} - \frac{3Am}{\hbar^2(\ell+1)^2}, \quad b = \left[ \frac{\hbar^4(\ell+1)^2(8\ell^2+37\ell+43)\delta^2}{2A^2m^2} - \frac{3}{2} \frac{(2\ell+5)}{(\ell+1)} \right],$$

$$c = \frac{\hbar^2(\ell+1)^3}{9Am} \quad (21)$$

Therefore, the analytical expressions for the lowest energy and full radial wave function of an ECSC potential are then given by

$$E_{n=0,\ell} = E_{n=0,\ell}^{(0)} + A\delta + E_0^{(1)} + E_0^{(2)} + \dots, \quad \psi_{n=0,\ell}(r) \approx \chi_{n=0,\ell}(r)u_{n=0,\ell}(r), \quad (22)$$

in which

$$u_{n=0,\ell}(r) \approx \exp\left(-\frac{\sqrt{2m}}{\hbar} \int^r (W_0^{(1)}(x) + W_0^{(2)}(x)) dx\right). \quad (23)$$

Hence, the explicit form of the full wave function in (22) for the ground state is

$$\psi_{n=0,\ell}(r) = \left[ \frac{2mA}{(\ell+1)\hbar^2} \right]^{\ell+1} \frac{1}{(\ell+1)^2} \sqrt{\frac{Am}{\hbar^2(2\ell+1)!}} r^{\ell+1} \exp(P(r)), \quad (24)$$

with  $P(r) = \sum_{i=1}^5 p_i r^i$  is a polynomial of fifth order having the following coefficients:

$$p_1 = \frac{(\ell+1)}{A} E_0^{(2)} - \frac{Am}{(\ell+1)\hbar^2}, \quad p_2 = \frac{9}{4} \frac{(\ell+2)}{(\ell+1)^2} c^2 d \delta^4, \quad p_3 = \frac{1}{6} c d \delta^4, \quad p_4 = \frac{1}{8} a c d \delta^4, \quad p_5 = \frac{1}{10} c d \delta^6, \quad (25)$$

in which  $d = b + \frac{6Am}{\hbar^2(\ell+1)^2\delta}$  and other parameters are given in (21).

## B. Excited state calculations ( $n \geq 1$ )

The calculations procedures lead to a handy recursion relations in the case of ground states, but becomes extremely cumbersome in the description of radial excitations when nodes of wavefunctions are taken into account, in particular during the higher order calculations. Although several attempts have been made to bypass this difficulty and improve calculations in dealing with excited states, (cf. e.g. [32], and the references therein) within the frame of supersymmetric quantum mechanics.



Using Eqs. (5) and (17), the superpotential  $W_n(r)$  which is related to the excited states can be readily calculated through Eqs. (18) and (19). So the first-order corrections in the first excited state ( $n = 1$ ) are

$$E_1^{(1)} = -\frac{\hbar^4 (\ell + 2)^2 (\ell + 7) (2\ell + 3)}{6Am^2} \delta^3,$$

$$W_1^{(1)}(r) \approx -\frac{\hbar (\ell + 2) \delta^3 r}{3\sqrt{2m}} \left\{ r + \frac{\hbar^2 (\ell + 2)(\ell + 3)}{Am} \right\}. \quad (26)$$

Consequently, the use of  $W_1^{(1)}(r)$  in the preceeding equation in (19) gives the energy correction in the second-order as

$$E_1^{(2)} \approx \frac{\hbar^6 (\ell + 2)^3 (\ell + 11) (2\ell + 3) (2\ell + 5)}{24A^2 m^3} \delta^4 - \frac{\hbar^{10} (\ell + 2)^6 (\ell + 3) (2\ell + 3) (7\ell^2 + 101\ell + 211)}{72A^4 m^5} \delta^6. \quad (27)$$

Therefore, the approximated energy value of the ECSC potential corresponding to the first excited state is

$$E_{n=1,\ell} = E_1^{(0)} + A\delta + E_1^{(1)} + E_1^{(2)} + \dots \quad (28)$$

The related radial wavefunction can be expressed in an analytical form in the light of Eqs (18), (19) and (22), if required. The approximation used in this work would not affect considerably the sensitivity of the calculations. On the other hand, it is found analytically that our investigations put forward an interesting hierarchy between  $W_n^{(1)}(r)$  terms of different quantum states in the first order after circumventing the nodal difficulties elegantly,

$$W_n^{(1)}(r) = -\frac{\hbar (n + \ell + 1) \delta^3 r}{3\sqrt{2m}} \left\{ r + \frac{\hbar^2 (n + \ell + 1)(n + \ell + 2)}{Am} \right\}, \quad (29)$$

which, for instance, for the second excited state ( $n = 2$ ) leads to the first-order correction

$$E_2^{(1)} = -\frac{\hbar^4 (\ell + 3)^2 (\ell + 2) (2\ell + 23)}{6Am^2} \delta^3,$$

$$W_2^{(1)}(r) = -\frac{\hbar (\ell + 3) \delta^3 r}{3\sqrt{2m}} \left\{ r + \frac{\hbar^2 (\ell + 3)(\ell + 4)}{Am} \right\}. \quad (30)$$

Thus, the use of  $W_2^{(1)}(r)$  in the preceeding equation (19) gives the energy correction in the second-order as

$$E_2^{(2)} = \frac{\hbar^6 (\ell + 2) (\ell + 3)^2 (2\ell + 5) (2\ell^2 + 45\ell + 153)}{24A^2m^3} \delta^4 - \frac{\hbar^{10} (\ell + 2) (\ell + 3)^5 (16\ell^4 + 474\ell^3 + 3879\ell^2 + 12118\ell + 12873)}{72A^4m^5} \delta^6. \quad (31)$$

Therefore, the approximated energy eigenvalue of the ECSC potential corresponding to the second excited state is

$$E_{n=2,\ell} = E_2^{(0)} + A\delta + E_2^{(1)} + E_2^{(2)} + \dots \quad (32)$$

For the numerical work, some numerical values of the perturbed energies of the  $1s$  and  $2s$  states, in the atomic units we take  $\hbar = m = A = 1$ , for different values of the screening parameter  $\delta$  in the range  $0 \leq \delta \leq 0.10$  are displayed in Tables 1 and 2, respectively. The results are consistent to order  $\delta^6$  with earlier results obtained by applying different methods in Refs. [9,22,23]. Further, we display the results for the energy eigenvalues of  $2s$ ,  $2p$ ,  $3s$ ,  $3p$ , and  $3d$  states in Tables 3 and 4. Our results are then compared with accurate energy eigenvalues obtained by other authors. Thus, through the comparison of our results with those of Refs. [9,10,22,23] for large  $n$  and  $\ell$ — values and small screening parameter values yields indeed excellent results.

On the other hand, we take  $A = \sqrt{2}$  and  $\delta = \sqrt{2}G$ . Cosequently, we compute the binding energies ( $-E_{n,\ell}$ ) of the lowest-lying states,  $1s$  to  $3d$ , for various values of  $\delta$ . Hence, the detailed analysis of the results in terms of various domains of parameters  $A$  and  $\delta$  of ECSC potential are displayed in Table 5. For further study of the bound-state energies and normalizations with analytical perturbation calculation in Table 6. We consider  $A = Z = 4, 8, 16, 24$  in order to cover the range of low to high atomic numbers. For low strength of  $A = Z$ , the energy eigenvalues nobtained are in good agreement with the other methods for low values of the screening parameter  $\delta$ . Obviously, when  $\delta$  is small the Coulomb field character prevails and the method has been adjusted to that. However, the results become gradually worse as  $A$  and/or  $\delta$  are large.

#### IV. CONCLUDING REMARKS

We have shown that the bound-state energies of the exponential cosine screened Coulomb (ECSC) potential for all eigenstates can be accurately determined within the framework of a new approximation formalism. Avoiding the disadvantages of the standard non-relativistic perturbation theories, the present formulae have the same simple form both for ground and excited states and provide, in principle, the calculation of the perturbation corrections up to any arbitrary order in analytical or numerical form.

Additionally, the application of the present technique to ECSC potential is really of great interest leading to analytical expressions for both energy eigenvalues and wave functions. Comparing various energy levels with different works in the literature we find that this treatment is quite reliable and further analytical calculations with this non-perturbative scheme would be useful. In particular, the method becomes more reliable as the potential strength increases.

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# TABLES

TABLE I. Comparison of bound energy eigenvalues for  $0 \leq \delta \leq 0.1$  for the  $1s$  state in atomic

units.

$\delta$	$1/N$ [22]	Dynamical [9]	Shifted $1/N$ [23]	$E_{n,\ell}$
0.01	-0.490 001	-0.490 001 0		-0.490 000 9
0.02	-0.480 008	-0.480 007 8	-0.480 007 83	-0.480 007 8
0.03	-0.470 026	-0.470 026 0		-0.470 025 9
0.04	-0.460 061	-0.460 060 9	-0.460 061 01	-0.460 060 8
0.05	-0.450 117	-0.450 117 4		-0.450 117 2
0.06	-0.440 200	-0.440 200 4	-0.440 200 57	-0.440 200 0
0.07	-0.430 313			-0.430 313 4
0.08	-0.420 461	-0.420 463 6	-0.420 463 86	-0.420 461 7
0.09	-0.410 647			-0.410 648 8
0.1	-0.400 875	-0.400 883 9	-0.400 884 21	-0.400 878 5

TABLE II. Comparison of bound energy eigenvalues for  $0 \leq \delta \leq 0.1$  for the  $2s$  state in atomic

units.

$\delta$	$1/N$ [22]	Dynamical [9]	Shifted $1/N$ [23]	$E_{n,\ell}$
0.01	-0.115 013	-0.115 013 5		-0.115 013 4
0.02	-0.105 103	-0.105 103 6	-0.105 103 61	-0.105 103 3
0.03	-0.095 334	-0.095 336 6		-0.095 334 6
0.04	-0.085 755	-0.085 769 0	-0.085 769 59	-0.085 762 1
0.05	-0.076 406	-0.076 449 7		-0.076 432 6
0.06	-0.067 311	-0.067 421 7	-0.067 426 08	-0.067 390 0
0.07	-0.058 482			-0.058 680 0
0.08	-0.049 915	-0.050 392 2	-0.050 408 25	-0.050 357 6
0.09	-0.041 598			-0.042 494 5
0.1	-0.033 500	-0.034 967 7	-0.035 004 67	-0.035 188 0



TABLE III. Energy eigenvalues as a function of screening parameter  $\delta$  for the  $2s$  and  $2p$  states in atomic units.

State	$\delta$	$E[10, 10]$ [10]	$E[10, 11]$ [10]	Pertur.[10]	Variational [10]	Shifted [23]	$E_{n,\ell}$
$2s$	0.10	-0.034 941	-0.034 941	-0.034 425	-0.034 935	-0.035 004 67	-0.035 188 0
$2p$		-0.032 469	-0.032 469	-0.032 042		-0.032 470 15	-0.032 673 3
$2s$	0.08	-0.050 387	-0.050 387	-0.050 222	-0.050 384	-0.050 408 25	-0.050 357 6
$2p$		-0.048 997	-0.048 997			-0.048 996 93	-0.048 993 9
$2s$	0.06	-0.067 421	-0.067 421	-0.067 385	-0.067 421	-0.067 426 08	-0.067 390 0
$2p$		-0.066 778	-0.066 778			-0.066 777 29	-0.066 761 1
$2s$	0.04	-0.085 769	-0.085 769	-0.085 767	-0.085 769	-0.085 769 59	-0.085 762 1
$2p$		-0.085 591	-0.085 591			-0.085 559 13	-0.085 552 0
$2s$	0.02	-0.105 104	-0.105 104	-0.105 104	-0.105 104	-0.105 103 61	-0.105 103 3
$2p$		-0.105 075	-0.105 075	-0.105 075		-0.105 074 64	-0.105 074 4

TABLE IV. Energy eigenvalues as a function of screening parameter  $\delta$  for the  $3s$ ,  $3p$  and  $3d$  states in atomic units.

State	$\delta$	$E[10,10]$ [10]	$E[10,11]$ [10]	Pertur. [10]	Variational [10]	Shifted [23]	$E_{n,\ell}$
$3s$	0.06	-0.005 461	-0.005 462	-0.004 538	-0.005 454	-0.005 666 38	-0.007 077 8
$3p$		-0.004 471	-0.004 472			-0.004 492 33	-0.005 405 8
$3d$		-0.002 308	-0.002 309			-0.002 313 56	-0.002 924 0
$3s$	0.05	-0.011 576	-0.011 576			-0.011 685 44	-0.011 952 3
$3p$		-0.010 929	-0.010 929	-0.010 538		-0.010 939 85	-0.011 111 7
$3d$		-0.009 555	-0.009 555	-0.009 292		-0.009 555 42	-0.009 694 0
$3s$	0.04	-0.018 823	-0.018 823	-0.018 707	-0.018 822	-0.018 867 16	-0.018 858 6
$3p$		-0.018 453	-0.018 453			-0.018 457 05	-0.018 450 5
$3d$		-0.017 682	-0.017 682			-0.017 682 08	-0.017 691 0
$3s$	0.02	-0.036 025	-0.036 025	-0.036 022	-0.036 025	-0.036 027 38	-0.036 021 3
$3p$		-0.035 968	-0.035 968	-0.035 965		-0.035 967 71	-0.035 964 0
$3d$		-0.035 851	-0.035 851	-0.035 849		-0.035 850 66	-0.035 849 0

TABLE V. Energy eigenvalues of the ECSC potential in units of  $\hbar = m = 1$ ,  $A = 2^{1/2}$  and  $\delta = GA$ .

G	State	$-E_{0,0}$	State	$-E_{1,0}$	State	$-E_{0,1}$	State	$-E_{1,1}$	State	$-E_{0,2}$
0.002	$1s$	0.996 000 0	$2s$	0.246 000 2	$2p$	0.246 000 1	$3p$	0.107 112 0	$3d$	0.107 111 4
0.005		0.990 000 2		0.240 003 4		0.240 002 4		0.101 125 5		0.101 116 0
0.010		0.980 001 9		0.230 026 9		0.230 019 3		0.091 221 7		0.091 147 5
0.020		0.960 015 6		0.210 206 6		0.210 148 9		0.071 928 1		0.071 361 7
0.025		0.950 030 2		0.200 395 3		0.200 285 7		0.062 648 5		0.061 566 5
0.050		0.900 234 4		0.152 865 2		0.152 099 1		0.022 223 5		0.014 137 4

TABLE VI. Energy eigenvalues of the ECSC potential for all states in units of  $\hbar = 2m = 1$ , and  $\delta = 0.2 \text{ fm}^{-1}$ .

$A$	$\ell$	$n$	$-E_{n,\ell}$	$A$	$\ell$	$n$	$-E_{n,\ell}$
4	0	0	3.207 029	16	0	1	12.825 303
8	0	0	14.403 752		0	2	4.023 139
	1	0	2.433 587		1	1	4.009 505
16	0	0	60.801 938	24	0	1	31.217 455
	1	0	12.818 287		0	2	11.279 786
24	0	0	139.201 31		1	1	11.269 899
	1	0	31.212 563		1	2	4.412 177
	2	0	11.249 961		2	1	4.380 887
					2	2	1.411 568